Regular Paper

Value Streams in Science & Technology: A Case Study of Value Creation and Intelligent Tutoring Systems

William B. Rouse[1,] * and Kenneth R. Boff[2]

[1]*School of Industrial and Systems Engineering, Georgia Institute of Technology, Atlanta,* GA 30332

[2]*Human Effectiveness Directorate, Air Force Research Laboratory, Wright-Patterson Air Force Base,* OH 45433

Received 27 August 2002; Accepted 18 December 2002
DOI 10.1002/sys.10038

ABSTRACT

Science and technology (S&T) involves a broad community of investors, sponsors, investigators, adopters, and end-users. This wide range of stakeholders adds value in a variety of ways, resulting in what are termed value streams. This article focuses on elaborating and formalizing S&T value streams. This formulation is evaluated in the context of a case study of computer-based intelligent tutoring systems. The value streams identified in this context span several decades of S&T investments, R&D in numerous organizations, and deployments in a variety of school settings. Insights gained from this case study enable proposing a general model of value creation in S&T. The phenomena embodied in this model suggest several central hypotheses. Approaches to evaluating these hypotheses are discussed. © 2003 Wiley Periodicals, Inc. Syst Eng 6: 76–91, 2003

Key words: science & technology, value strategies, value creation, research & development, intelligent tutoring systems, value streams

1. INTRODUCTION

This article builds upon our earlier framework for identifying the nature of value, determining how to provide value to stakeholders, and formulating enterprise value

---

* Author to whom all correspondence should be addressed (e-mail: bill.rouse@isye.gatech.edu).

Systems Engineering, Vol. 6, No. 2, 2003

strategies [Rouse and Boff, 2001]. Key to this framework is the concept of value streams. Our goal in this article is to formalize the notion of value streams and illustrate this representation for a particular case study.

Value is defined by the *Merriam-Webster Collegiate Dictionary* as relative worth, utility, or importance; the monetary worth of something, i.e., its marketable price; and a fair return or equivalent in goods, services, or money for something exchanged. These definitions are compatible with the construct of value streams articulated here.

Beyond defining value, it is important to describe the characteristics of value as provided by organizations:

- Value focuses on organizational outputs (or outcomes), rather than inputs.
- Value relates to benefits of outcomes, rather than outcomes themselves.
- Value implies relevant, usable, and useful outcomes.

This article focuses on value creation in science and technology (S&T). Our definition of S&T includes the whole community of investors, sponsors, investigators, adopters, and end-users. Research and development (R&D) denotes one of the classes of activities within broadly-defined S&T. As is very clear from the case study reported in this article, value is created in S&T by many more activities than just R&D. Upstream formulation and management of balanced investment portfolios and downstream management of technology transition are particularly notable examples of other value-creating activities.

S&T outcomes have traditionally been characterized in terms of technologies developed and deployed. For some types of enterprises, deployment implies new processes and products that yield profits, which may be due to increased prices, decreased costs, and/or increased revenues. To the extent that the time series of likely profits and required investments can be projected, value can be monetized in terms of the net present value of this time series.

The difficulty with this approach is that technology deployment often involves downstream decisions that are contingent on conditions at the time when decisions are made. Further, technologies may not be deployed for market and/or competitive reasons, independent of the success of the R&D efforts associated with these technologies. For these reasons, we have often found it useful to characterize S&T outcomes in terms of the number of viable "technology options" created. Technology options can be described as valid fundamental knowledge, translated into usable forms, and provided in useful manners.

The value of technology options can be assessed using option pricing models [Rouse et al., 2000]. The free cash flow projections needed as inputs to these models can be profits or cost savings, the former primarily meaningful for private sector enterprises and the latter usually meaningful for all enterprises. For public sector enterprises, it is also possible to view increased tax receipts as the cash flow resulting from increased investments, e.g., in training and education, as discussed in this article.

Thus, overall value includes both economic value—expressed in terms of the discounted cash flow of near-term benefits—and the strategic value of technology options that provide, at the very least, hedges against possible futures [Boer, 2002]. While this article does not focus on the monetization of value, it is important to indicate how this can be done.

Enhancing value requires consideration of the processes whereby value is provided to stakeholders. The flows of value added by processes can be termed value streams. Understanding and managing these value streams involves assessing how current processes do or do not add value, and redesigning processes to insure that the value/cost proposition for each process makes sense. Assessment and redesign usually lead to reallocations of resources to activities and projects that will enhance value.

Our earlier paper characterized value strategies using the dimensions of quality, productivity, and innovation. Quality traditionally relates to the reliability, fit and finish, etc. of products and responsiveness, friendliness, etc. of services. Productivity concerns efficient use of resources that enables lower costs and attractive prices. Innovation deals with the extent to which offerings provide new and possibly unique benefits. Value strategies are intended to increase value, which can be monetized as discussed earlier.

The dimensions of quality, productivity, and innovation also apply to S&T. Quality relates to readiness for technology transition in terms of technology maturity and reliability, availability of test results and documentation, etc. Productivity concerns the efficiency of resource utilization relative to creating S&T outcomes in timely manners. Innovation ranges from incremental to disruptive technologies, which relates to levels of risk. Risks tend to increase costs—to assure acceptable levels of success—but high productivity can mitigate against such consequences.

In general, an S&T value strategy—in terms of quality, productivity, and innovation—should dovetail with the overall enterprise's value strategy. This is particularly true for innovation. Productivity is more likely to be inherently aligned because of the extent of cost sensitivity in the enterprise's culture, policies, and procedures. There may be less enterprise-wide uniformity in quality—for example, high quality process technologies may be needed to yield undifferentiated product quality at very low costs.

Formulation and implementation of value strategies are addressed in some depth in the earlier article [Rouse and Boff, 2001]. This includes a somewhat detailed treatment of the dimensions of quality, productivity, and innovation. While we will do not revisit this material here, we did employ these three dimensions as key elements of one of the interview questions in the case study reported below. Thus, we return to these dimensions in discussing the results of the case study.

This article focuses on elaborating and formalizing the notion of value streams. This formulation is evaluated in the context of a case study of computer-based intelligent tutoring systems. The value streams identified in this context span several decades of S&T investments, R&D in numerous organizations, and deployments in a variety of school settings. Insights gained from this case study enable proposing a general model of value creation in S&T. The phenomena embodied in this model suggest several central hypotheses. Approaches to evaluating these hypotheses are discussed.

2. VALUE STREAMS

Our pursuit of the value construct began with explorations of cost/benefit analysis for R&D investments [Rouse, Boff, and Thomas, 1997; Rouse and Boff, 1999]. These explorations included broader consideration of R&D/technology management [Rouse and Boff, 1998], as well as more focused topics such as knowledge mapping [Rouse, Thomas, and Boff, 1998] and option pricing models for valuation of technology investments [Rouse et al., 2000]. These efforts culminated in the more recent work on value strategies [Rouse and Boff, 2001].

Most recently, it has become apparent that the value construct should be formalized. In particular, it is useful to have an agreed-upon representation of value streams to assure that all key elements are considered, as well as enable agreement on standard terminology. Indeed, terminological ambiguity often causes useful constructs to be adopted more slowly than otherwise possible. The representation proposed here hopefully mitigates these difficulties and also provides insights into how value streams can be dysfunctional.

An agreed-upon representation can also be invaluable for organizational design and redesign. The initial steps include mapping and assessing the value flow in an organization. Subsequent steps often focus on redesigning the organization to enhance value flow. In later discussion of a generalized model, several types of enhancements are noted.

Value streams are composed of process stages where value is added. Each stage can be represented as shown in Figure 1. Stages receive inputs from upstream users and provide outputs to downstream users. Adding value consumes resources and is influenced by various controls. Lack of resources and controls tends to undermine value.

Stages can be connected in series and/ or parallel to depict overall value streams as illustrated in Figure 2. Upstream users may provide direct inputs to downstream users—for instance, in terms of technology options—or possibly provide controls or resources as shown in Figure 2. For example, a procurement planning activity occurring in parallel with S&T may enable downstream transition of the outputs of S&T to fielded solutions.

End users, and other intermediate users, influence stages via controls by requesting and/or approving the activities associated with a stage or, at least, the products expected of a stage. Events such as unexpected breakthroughs or demands can also exert control. Such breakthroughs may, for example, provide new benchmarks for innovation, effectively redefining that dimension of value.

Stages consume resources including the people associated with the stage, budgets, and facilities. Stages also consume knowledge, which may or may not be available, and may or may not come from other users in the value stream. Finally, stages consume time, both for performing the activities associated with a stage and while waiting for resources (e.g., budget or knowledge) and controls (e.g., approvals).

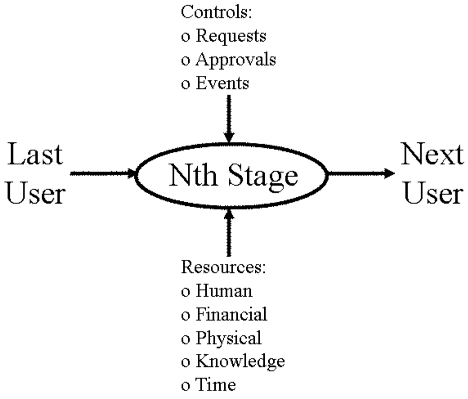

Figure 1. Representation of a stage of a value stream.

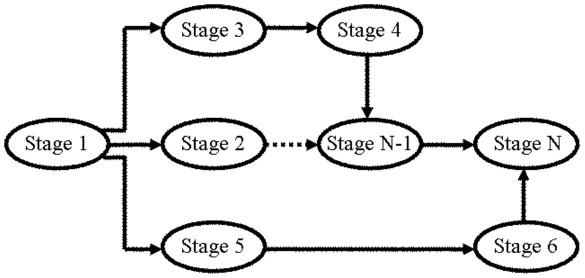

Figure 2. Example value stream.

As noted earlier, value streams can be evaluated in terms of quality, productivity, and innovation. An overall S&T value stream—or any stage of a value stream—can yield less than maximum value by, for instance, creating poorly documented research results (poor quality), requiring investments for which the returns are inadequate (poor productivity), and/or producing the "same old stuff" which downstream users find decreasingly useful (lack of innovation).

Value streams can be dysfunctional for structural reasons also. In particular, controls and resources can be "miswired," creating delays and inefficient uses of resources. For example, follow-on procurements may be delayed. As another example, human resources may not be available when needed. The case study reported here exhibits aspects of these problems.

Beyond stage and structural inadequacies, value streams may lack adequate feedback control systems for adapting the flow of value to changing environmental conditions. For example, end users and/or their priorities may change. Technology generations may change or breakthroughs occur. The feedback system should be able to adjust controls and thereby allocations of resources in response to such changes.

Thus, we can assess the processes and structures underlying value streams in terms of:

- Quality, productivity, and innovation of stages, individually and collectively.
- Existence and timing of structural relationships necessary to enable stages to deliver quality, productivity, and innovation.
- Existence, flexibility, and adaptivity of feedback control systems in response to environmental changes.

Inadequacies in any of these areas can lead to low yield, late delivery, and excessive investments, any of which can culminate in decreased economic and/or strategic value. At the very least, redesign of value streams, and perhaps the overall organization, should enable the same yield, faster and cheaper.

It is important to note that the value stream construct just outlined is not dissimilar from related systems engineering concepts. Indeed, the idea of a value stream is borrowed directly from work in lean thinking [Womack and Jones, 1996; Kessler, 1999]. Life cycle systems engineering models [Sage, 1995, Patterson, 1999] and IDEF models [Sage, 1995; Kusiak and Larson, 1999] can also be used to depict value streams. In fact, there is a rich heritage of systems-oriented representations of relationships, feedback, uncertainty, and so on that Figures 1 and 2 draw upon [Sage and Rouse, 1999].

The following case study illustrates the use of the representation of value streams just outlined. The results of this case study also enable identifying potential general characteristics of S&T value streams that both offer explanations of past shortfalls in value and suggest mechanisms for avoiding such difficulties.

3. CASE STUDY

Two criteria were primary in selecting a domain for this case study. First, the domain had to be readily understandable by a wide range of readers, as well as workshop participants where this material is to be employed. This eliminated a wealth of esoteric military technologies that only specialists would fully understand. Of course, information on the evolution of such technologies would have been quite difficult to access.

The second criteria was that S&T activities in the domain had to be traceable from basic research to applied development and deployment. Further, obviously, we had to be able to identify and access information on the flow of value across the stages of the value stream. Such information would inevitably cover many decades of activities and outcomes.

Training in general, and Intelligent Tutoring Systems (ITS) in particular, satisfied these two criteria. Beyond being readily understandable, the evolution of ITS started with many years of basic research in psychology, education, and computing. More recently, applied research has paralleled the basic research, especially as computing has become less expensive and more pervasive. Most recently, advanced development and deployment have been the foci. The following sections outline this evolution.

It is important at the outset to note that the idea of using computers to deliver instruction has been explored for several decades, with sponsorship most notably from the National Science Foundation (NSF), the military service research agencies—Air Force Office of

Scientific Research (AFOSR), Army Research Institute (ARI), and Office of Naval Research (ONR)—and the Defense Advanced Projects Research Agency (DARPA).

3.1. Behavioral Science Foundations

The approaches adopted for these efforts paralleled developments in behavioral science which, naturally, strongly influenced views of learning and hence instruction. The behaviorism of Watson [1914] and, more importantly, Skinner [1938] emphasized the rote learning of stimulus-response rules. This paradigm placed off limits whatever happens in people's heads.

The emergence of cognitive psychology, perhaps best typified by Miller's classic paper [1956] on "the magic number seven," advocated an information processing view of human performance and researched the nature of human information processing. More recently, cognitive constructs such as "mental models" have been invoked to explain people's abilities to anticipate and explain [e.g., Rouse and Morris, 1986]. Computer-based instruction, in this paradigm, could be used to create and enhance mental models.

Mathematical psychology attempted to bring the formalism of equations to understanding human learning, decision making, and problem solving [e.g., Krantz et al., 1974]. Some of this work focused on learning of mathematics, e.g., logic. This provided a fertile area for study of computer-based approaches to mathematics instruction [Suppes, 1981].

Newell and Simon [1972] pioneered cognitive science and an information processing paradigm based on "production systems," sets of if-then rules hypothesized to underlie human problem solving. Computer-based instruction thereby involved fostering learning of experts' production rules, which enabled attaining expert performance. Cognitive science provides the underpinnings for Intelligent Tutoring Systems, the focus of the case study reported here.

3.2. Instructional Systems

The paradigm of behaviorism strongly influenced how learning was viewed and, hence, instruction considered. Human performance was seen as focused on task performance in terms of explicit procedures for the steps associated with tasks. Instructional System Design (ISD) became the favored methodology for assuring that people learned tasks, steps, and procedures [e.g., Gagne and Briggs, 1974]. ISD focuses on defining learning objectives and target behaviors, as well as approaches to instruction.

Computer-based instructional systems developed at that time included embedded training for the Air Force's SAGE system—called the System Training Program [Rowell and Streicht, 1964]. Also in that time frame was the University of Illinois' PLATO system [Bitzer, Braunfield, and Lichtenberger, 1961]. These two systems emphasized procedural learning and, in contemporary terms, would be called "page turners."

Developments in cognitive science and, in parallel, artificial intelligence, led to intelligent computer-based instruction. Sleeman and Brown [1982] chronicle the development of many early intelligent instructional systems, starting with the pioneering work of Carbonell [1970]. Rouse [1987] reviews a variety of specific instructional systems developed and fielded in the 1980s, including the Generalized Maintenance Training System, Sophie, Simulation-Oriented Computer-Based Instruction, and Steamer.

The late 1980s and early 1990s saw much greater emphasis on the cognition of learning and expert performance. A wealth of studies and systems emerged, many of which are described in Polson and Richardson [1988], Pstoka, Massey, and Mutter [1988], Burns, Parlett, and Luckhardt [1991], and Regian and Schutte [1992]. These edited collections chronicle the development and evaluation of Intelligent Tutoring Systems, particularly by the Air Force. The functional nature and experiences fielding ITS are discussed below.

Current development emphasizes web-based delivery of instruction—termed "e-learning." Pontin [2002] discusses the e-learning market and the large amounts lost by the players in this market, except for corporations and academia where higher prices have enabled better offerings. He argues for "blended" classes that employ both e-learning and human instruction. Such blending, he asserts, will eventually result in e-learning losing its unique identity and simply being an everyday element of education.

3.3. Evaluation of Instruction

While computer-based instruction seems like an obvious idea, particularly in retrospect, there have been two decades or more of research devoted to understanding the impact of such instruction and how this impact is achieved. Early initiatives include Suppes' [1981] studies of computer-aided instruction at Stanford. Rouse [1987] reviews the efforts to evaluate a range of early instructional systems based on computer simulations and/or artificial intelligence.

Of particular relevance to this article are the efforts at Carnegie Mellon University (CMU) and the Air Force Research Laboratory (AFRL) focused on development, deployment, and evaluation of ITS in high schools and military units. The experiences associated with these two efforts were a primary focus of this study. The CMU and AFRL Intelligent Tutoring Systems incorporated several expert system-based elements:

- Rule-based models of expert performance in the domain of interest, e.g., algebra or LISP programming.
- Reasoning about the student's current knowledge state relative to the expert model's state.
- Instructional interventions (e.g., feedback and help) based on the path and nature of student's deviations from the expert's state.

Anderson et al. [1995] have developed and evaluated ITS based on their ACT theory of cognition. This has included tutors for geometry, algebra, and the LISP programming language. An impressive series of classroom evaluations showed that the geometry tutor increased average grades by 14 points (more than one standard deviation), the algebra tutor yielded no improvement, and the LISP tutor resulted in faster performance (30–64%) and higher scores (30–43%).

Anderson et al. [1995, p. 204] indicate, "The principle reason for enthusiasm for our tutors within the Pittsburgh Public School System is motivational gains, not achievement gains." They also propose eight principles for ITS:

- Represent student competence as a production set.
- Communicate the goal structure underlying the problem solving.
- Provide instruction in the problem-solving context.
- Promote an abstract understanding of the problem-solving knowledge.
- Minimize working memory load.
- Provide immediate feedback on errors.
- Adjust the grain size of instruction with learning.
- Facilitate successive approximations to the target skill.

Corbett, Koedinger, and Hadley [2001] chronicle the deployment of Anderson's tutors, indicating that, by 1999–2000, "about 15,000 students in about 150 U.S. schools use the (algebra) tutor 1–2 days a week." p. 1 Ongoing evaluations have shown that ITS improve performance by roughly one standard deviation. This is about half of what human tutors can achieve and two to three times the impact of conventional computer-assisted instruction. They also indicate that ITS transform the teacher-student relationship, with the teacher becoming less a stand-up lecturer and more of a one-on-one coach. This ongoing effort has been sufficiently long-running to report that "[t]he total abandonment rate over the past five years of approximately 4% is far less than the textbook industry 'churn' rate of about 15%." p. 20

Roughly in parallel with Anderson et al. [1995], the Air Force Research Laboratory has conducted an ambitious ITS initiative involving development and evaluation of a range of ITS. Twenty studies of the impact of ITS for word problem solving and writing found average improvements of 29% and 26%, respectively [TutorTek, 2001]. A representative study in this set is Wheeler and Regian's [1999] large-scale study involving 632 students and 20 teachers in 7 high schools in 3 states. Concrete and abstract reasoning scores for word problem solving improved 31% and 20%, respectively, with the ITS for word problem solving vs. 19% and 15% for the placebo (computer-based but no instruction) and 22% and 11% for the control group (traditional instruction).

The data on the impact of ITS are rather impressive. Results of numerous independent studies conducted by several independent investigators show substantial improvements for high school students learning algebra, geometry, word problem solving, writing, and so on. Fletcher [2001] summarizes this range of results with a "rule of three thirds." Use of ITS reduce costs by 1/3 *AND* reduce time by 1/3 *OR* increase achievement by 1/3. While this does not include the costs of developing ITS, if these costs are spread across thousands of students per year over several years, development cost per student hour is not a major factor. A similar economic argument underlies textbook publishing.

3.4. Military Adoption

As later data indicate, defense agencies—particularly DARPA, AFOSR, and ONR—have invested very substantially in ITS. Numerous studies have documented the returns on these investments in terms of proven instructional capabilities and payoffs [Fletcher and Rockaway, 1986; NRC, 1997; Fletcher, 1999, 2002]. However, there has been little, if any, deployment of ITS in defense schools. Less than 2% of Department of Defense (DoD) courses employ instructional technology [Fletcher, 2001].

A variety of reasons have been suggested for this lack of impact. A recurring comment is that the impact of ITS on instructional staff is quite often in conflict with traditional DoD instructional cultures. ITS can enable reducing the number of instructors which may be an unwanted result in some DoD organizations. ITS work best when instructors act as coaches—"guides on the side rather than sages on the stage"—but this can be inconsistent with typical rank-oriented social structures in the services.

Beyond these anecdotal explanations, the complicated processes for technology deployment in DoD can make adoption quite difficult for disruptive—as opposed to incremental—technologies. In an interview study of senior S&T managers in the Air Force, Army, and Navy, ITS were offered as a success story for the Air Force and a failure story for the Navy [Rouse and Boff, 1994]. The difference between success and failure was primarily attributed to champions who were able to circumvent typical organizational processes and practices. We return to this observation when discussing the results of the present study.

Despite these difficulties, it appears that DoD's Advanced Distributed Learning initiative [DoD, 1999] will be able to gain the benefits of several decades of investments in ITS. Computer and communications technologies are now much less expensive and much more pervasive. Another factor in this emerging adoption may be behavioral and social expectations that computer-mediated instruction is of obvious value.

3.5. Impact of Changing Technology

An essential element of this brief history of ITS is the backdrop of ongoing technological change. This decades-long story began with reliance on special purpose computers, e.g., SAGE, and evolved to time-sharing, minicomputers, workstations, microcomputers, and Internet. In parallel, software evolved from Fortran programs compiled from cards to object-oriented programming and agent-based systems in C++ and Java.

These changes have enabled less expensive, more powerful ITS. At the same time, however, these changes have resulted in technology upgrades consuming a significant portion of investment resources. Such upgrades have often created support problems for the installed base of legacy ITS. As the results of the following study show, successfully consuming technological change was an ongoing significant factor.

3.6. Interview Methodology

The foregoing provided the background for an interview study of key stakeholders involved in the conceptualization, development, evaluation, and deployment of ITS. The goal of this study was to identify the nature of and relationships among the elements of the value stream for ITS. Of particular interest was the extent to which the value stream construct could provide insights into how to manage value streams explicitly and, hopefully, better.

To infer the characteristics of each stage of a value stream, one can begin at the end where the value has been delivered (e.g., a solution fielded or deployed, providing ongoing benefits) and work backwards to identify activities associated with each stage, resources and controls involved with these activities, and upstream users upon which the stage depended. One then repeats the sleuthing with these upstream users becoming the interviewees, i.e., the people performing the activities associated with the earlier stage(s).

This type of sleuthing is best done via structured interviews—unless the requisite information has been fortuitously captured and archived as development, evaluation, and deployment occurred. Such information was not readily available for the ITS initiatives of interest. Figures 1 and 2 provided the basis for the structured set of interview questions shown in Figure 3.

1. What was your involvement and your organization's involvement in the process of creating Intelligent Tutoring Systems?
2. What activities did you and your organization perform, and over what time periods did these activities occur?
3. Who were the key stakeholders in this overall effort and how did they influence your involvement and activities?
4. What requests, approvals, or other events affected your abilities to perform these activities?
5. What resources were required for these activities and from where did they come?
6. What inputs did you need and what organizations and people did you depend on for these inputs?
7. What delays did you experience in approvals, budgets, or necessary inputs, and what were the impacts of these delays?
8. What changes did you experience in the course of this effort and how did you respond to these changes?
9. How would you characterize the quality, productivity, and innovation of the value you and your organization delivered?
10. What other insights can you provide to elaborate your answers thus far or perhaps touch on other important issues?

Figure 3. Questions for structured interviews.

These questions provided the overall framework for a set of telephone interviews with key stakeholders.

Ten people were interviewed. Several of these people are top researchers and opinion leaders in the ITS field. It is important to note that this interview methodology did not focus on selecting a representative sample of possible interviewees, perhaps randomly selected. Instead, we first focused on key participants who could provide multiple rich perspectives on issues and events surrounding the emergence and maturation of ITS. Later interviewees were other key participants identified by earlier interviewees. Rather than statistical analysis, the goal was sleuthing out exactly what happened and obtaining complementary and, hopefully, confirming views whenever possible. Care was also taken to include people involved with the full spectrum of the value stream, ranging from basic research to applied research and deployment. The resulting demographics of the interviewees are summarized in the next section.

All interviews were conducted via telephone. In a few cases there were multiple conversations as later interviewees raised issues and questions about which earlier interviewees' perceptions and opinions were needed. Data were captured as handwritten interview notes. These notes often included references to documents and websites that provided more in-depth documentation of studies and results.

Handwritten notes were compiled in a database with fields for interviewees, questions, and responses. Responses were also classified in various content categories. The database was then sorted by these categories. Viewing the spectrum of entries for a given category enables refining the category label and, in some cases, reclassifying responses. Such changes prompt resorting of the database. This iterative process leads to better defined categories and clearer discriminations and interpretations. This overall approach yielded the results and interpretations presented in the next section.

4. RESULTS

The first interview question concerned interviewees' involvement in ITS. Overall, three interviewees had been S&T sponsors, three served as academic researchers, four worked as government researchers, and two were high school teachers. Note that the total exceeds ten because some interviewees had different roles at different times, e.g., initially as an academic researcher and subsequently as a government researcher or sponsor.

The second question addressed the time period of interviewees' initial involvement and the nature of their activities. This concerned the time period of the interviewee's initial involvement in the field, rather than that of their organizations, at that time or currently. Two people provided extensive histories of the field, starting with their initial experiences in the 1960s and 1970s. The other eight people mainly were knowledgeable of their own involvement and their organizations in the 1980s and 1990s.

Interviewees' activities during their initial involvement in the ITS field included R&D (6 responses), relationship development (5), negotiating budgets (5), project management (6), and delivery of instruction (2). Thus, all of the researchers reported significant involvement in activities beyond R&D. They typically indicated that a surprising amount of time was devoted to these non-R&D activities, often not by choice but of necessity. The level of commitment needed for these non-R&D activities was often noted as unanticipated.

Figure 4 indicates interviewees' perceptions of key stakeholders. This represents their perceptions of which stakeholders most affected their organization's overall

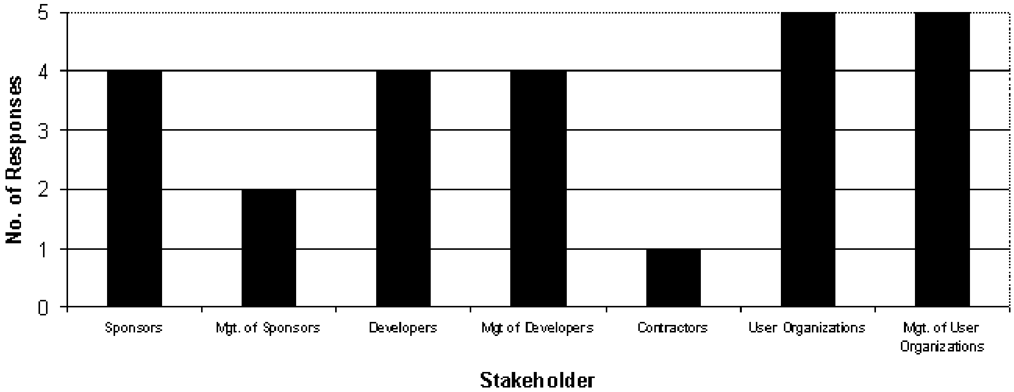

Figure 4. Key stakeholders in the overall ITS effort.

ITS endeavor rather than being limited to the stakeholders that most affected their own activities. This broad set of stakeholders is of particular interest because their relative importance changes for the results of later questions.

It is useful to clarify the role of contractors in these ITS efforts. The contractors were primarily on-site R&D support contractors and small research companies. Unlike much DoD contracting, these efforts did not involve soliciting bids from contractors to build systems that meet specified requirements, and subsequently contractors delivering the resulting system. Thus, contractors were not as "key" as would be typical for traditional acquisition contracts.

The fourth question concerned central requests and approvals throughout the ITS efforts. Overall, getting money into the R&D process (i.e., from sponsors and managers) and technology out of this process (i.e., adopted for deployment) were the primary approval-related issues. Requests and approvals for R&D funding reflected four of the responses, while six included requests and approvals for adoption agreements, equipment transfers, budgets for deployment, and organizational changes.

The fifth question addressed resources required and sources. Almost all the money came from DARPA, AFRL, AFOSR, ONR, and NSF. Three of the interviewees indicated $5million/year and four reported $5–10 million in total. This difference between $5M/year and $5–10M reflects the difference between consuming organizations, needing so much per year, and investing organizations that were typically one of several investors over the life of the endeavor. People as resources were indicated by four of interviewees as key resources and money was seen as the means to this end.

Figure 5 summarizes the inputs needed throughout the ITS initiatives. Once programs and budgets were approved, management played much less an ongoing role than indicated for the earlier "key stakeholders" question—see Figure 4. Quite simply, management inputs were seen to be much less important once resources were committed. User organizations differed in this regard in that ongoing support for deployment was needed. While investors could "launch" a technology, user organizations had to live with the technology.

Figure 6 provides a summary of the nature of delays experienced throughout the ITS efforts with which interviewees were involved. There were few delays due to S&T issues. Instead, delays were primarily due to management and administrative issues. Note that interviewees interpreted delays as time unnecessarily lost. Obviously, the R&D and deployment processes inherently consumed substantial amounts of time. However, this time was seen as all value added, while the delays were seen as value neutral, at best.

The eighth question concerned changes experienced throughout these ITS efforts. Four interviewees reported that technology changed very substantially during this extended time period, changing from being expensive and often a constraint to being inexpensive and more often an enabler. Technology upgrades were difficult for the deployment sites (high schools) due to budget constraints. Four interviewees indicated that the tutors also changed significantly during the course of this endeavor, mostly due to user feedback but also due to technology changes. The changes of the tutors included those due to fundamental insights into the nature of instruction provided by the deployment data and experience.

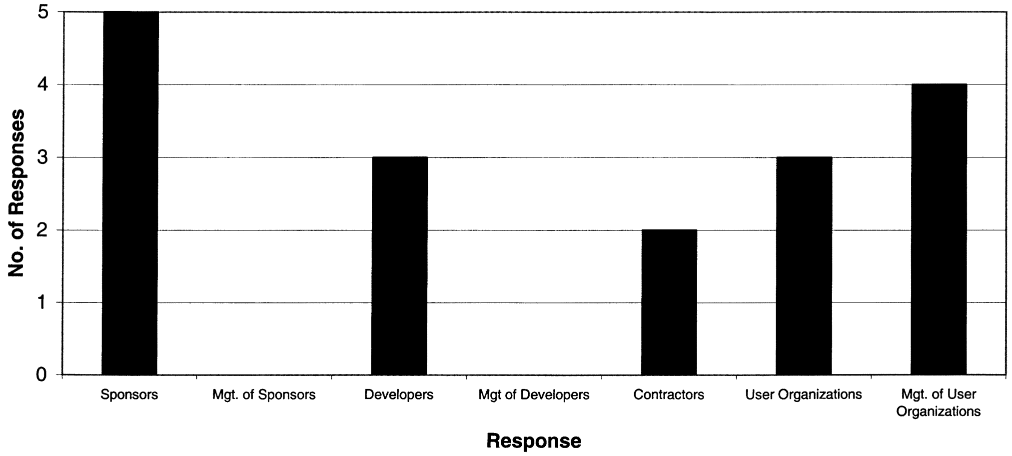

Figure 5. Sources of inputs critical to the ITS initiative.

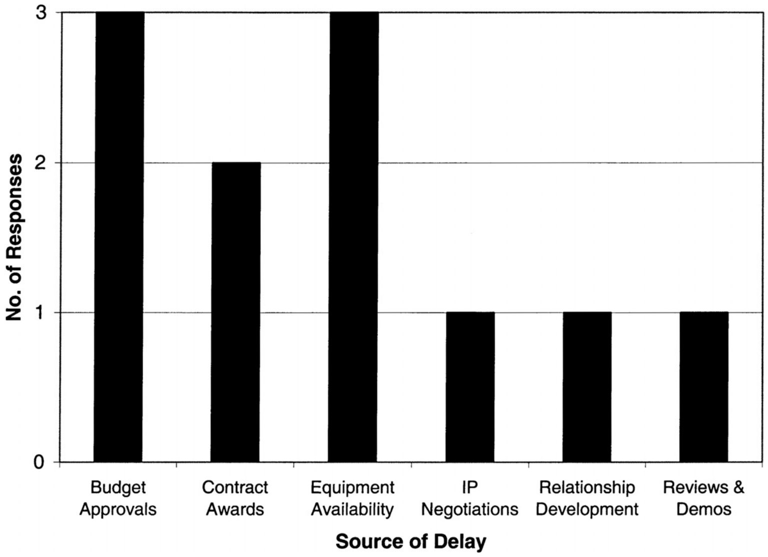

Figure 6. Nature of delays experienced throughout ITS initiative.

The ninth question addressed interviewees' perceptions of the quality, productivity, and innovation associated with the ITS initiatives with which they were associated. Interviewees rated the quality dimension of the value delivered as good to very high relative to typical products of R&D, as opposed to commercial off-the-shelf software. Concerning perceptions of the productivity dimension of the value delivered, some interviewees perceive ITS as expensive relative to dollars per instructional hour. Nevertheless, most perceived the R&D efforts in this area as providing significant "bang for the buck." Relative to perceptions of the innovation dimension associated with the value delivered, most interviewees felt that the investment in ITS did not have the impacts that were possible and justified, particularly for military user organizations. They tended to view this as an organizational and cultural phenomena rather than a shortcoming of the technology.

Note that it was not possible to address quality, productivity, and innovation quantitatively in this study. The several decades of efforts reported by interviewees includes numerous studies and several different types and generations of ITS. Consequently, we had to ask interviewees about their perceptions across studies and ITS.

The last question concerned other insights that interviewees gained from their experiences with the ITS initiatives. Five of the interviewees tended to perceive that technology transfer is much more complicated, time-consuming, and expensive than they had anticipated before this experience. Two argued for adopting a much longer view to assure that technology transfer plans are formulated, maintained, and executed. Three interviewees commented on users wanting tutors rather than tools for creating tutors, as well as the limited nature of typical tutors today, e.g., just page turners, lacking in abilities to generate, rather than just retrieve, instruction.

Finally, it is useful to discuss why these results could not be monetized, perhaps in terms of option values for enabling technologies and system prototypes. These ITS investments could certainly be framed as options [Rouse, Boff, and Thomas, 1997]. However, data needed for projected cost savings and actual investments were not available. It is quite possible that the requisite data exist somewhere, but such data are not readily identifiable and accessible.

5. S&T VALUE STREAM

Drawing upon the elements of Figures 4 and 5, the S&T value stream inferred for the ITS case study is shown in Figure 7. Note that value is created by upstream formulation of investment portfolios as well as downstream activities to deploy technologies—thus, research and development were far from the sole sources of value. Deciding what to do provides value and making sure that value is deployed also provides value.

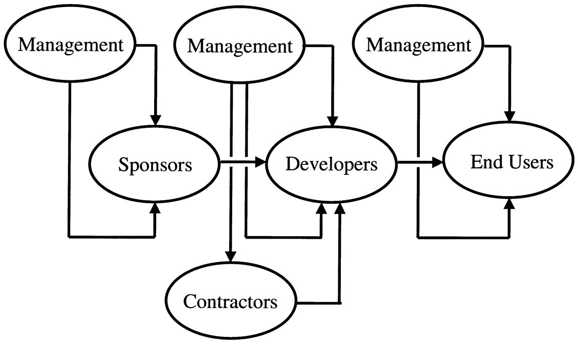

Figure 7. Kernel of the S&T value stream for ITS.

The "kernel" depicted in Figure 7 repeated itself many times throughout the "ITS story" outlined above. Thus, an overall value stream, stretching across decades, could be created with specific initiatives noted in the ovals of Figure 7. Such a depiction would emphasize the ample opportunities for diminished value across many sponsors, projects, and years, due to, for example, delays of requests and approvals.

Note that "management" in Figure 7 often provides both the controls and the resources. This does not necessarily imply that the same decision makers have purview over both controls and resources. Indeed, the lack of this common purview often caused delays and potentially diminished value.

- Management and Sponsors include for this case study DARPA, AFOSR,[1] ONR and NSF.
- Management and Developers include AFRL and support contractors for the Air Force initiatives; the parallels for the CMU efforts were not assessed.
- Management and End Users include high school administrators and teachers; the parallels for military end users were not available.

It is very important to note that essential elements of the value stream in Figure 7 were non-DoD organizations, including both contractors and public high schools. In our earlier case study of Cockpit Automation Technology [Rouse, Boff, and Thomas, 1997], there were a large number of non-DoD organizations in the value stream. We have found that value streams often cross organizations and sectors of the economy.

A profound implication of the cross-organizational nature of value streams is the inherent inability of any one organization to be "in charge" of a value stream. Seldom is "command and control" management effective for entire value streams. Instead, primary attention must be given to alignment of motivations and incentives across participants. This is needed to assure that it is in the best interests of the full spectrum of participants to contribute value as needed.

Considering the foregoing empirical results in the context of the model in Figure 7, time-consuming requests and approvals usually involved management decision making associated with controls and resources. Interviewees often perceived that the time required for decisions was unnecessarily extended. Interestingly, this was not perceived to undermine value—in terms of quality, productivity, or innovation—but simply delayed delivering value.

In contrast, the time and other resources devoted to negotiating and executing plans for deploying ITS—the right-most third of Figure 7—was perceived as impacting productivity, often taking large portions of the attention of key personnel. This was due in part to not having realized in advance the time consuming nature of such activities. Another factor was the backdrop of frequently advancing technology. A few interviewees noted that the installed base of legacy ITS made it difficult to deploy the latest innovations.

The overall results of this case study can be summarized as follows. First, considering the breadth of the time period and activities covered, it is difficult to conclude that any particular effort did or did not provide high value. In contrast, the overall process took much too long to yield much too little for DoD. Thus, the efficiency and effectiveness of value creation was undermined by deficiencies in the explicit management of the value creation process. In particular, upstream portfolio creation and management seemed to work fairly well, while downstream management of deployment encountered several difficulties.

Specifically, significant time was consumed by delays in approvals of programs, budgets, and equipment. Deficient yield was due to technology acceptance problems with DoD end users. A second-order but nevertheless very significant factor, due in part to the extra time, was the effects of technology evolution. Dealing with this ongoing evolution consumed resources and more time. This additional loss of time can perhaps be viewed as a third-order effect.

This value creation case study can also be viewed in terms of the options created by the investments. Most of the early R&D did not create deployable systems. Instead, these efforts demonstrated that certain capabilities were feasible and showed how to make them work. Thus, they created technology options in the form

---

[1] AFOSR is now part of AFRL. During the time that most of this S&T was pursued, AFOSR was independent. Further, AFRL was not yet formed and AFHRL (Air Force Human Resources Laboratory) was the name of the organization pursuing the ITS initiative.

of knowledge and competencies more than prototypes and patents.

Some of the work in the middle years—the Navy's efforts—ran into acceptance problems and options were not exercised. The Air Force exercised the technology options created by the Navy [Rouse and Boff, 1994], also encountering acceptance problems, but moving instead to high schools. In addition, these options were also exercised by NSF via Anderson's deployment of tutors in high schools [Anderson et al., 1995].

Most recently, the ADL program is exercising options created by these several streams of R&D, as well as deployment experiences. Were we to consider the time value of money, e.g., discounted cash flows, due to DoD's very much delayed exercising of these options, the option value back in the 1960s—for options to be exercised in the 2000s—would be quite low. However, *net* option value might still be positive, given productivity changes over the past 40 years.

An interesting element of this public-sector case study is that the ITS technology options could, in effect, be given away but still retained. In other words, the Air Force, Navy, NSF, etc. can all exercise the same options. In fact, those exercising the options early may improve the option value for those exercising options later—by creating more capable technologies that enable greater savings and, hence, larger cash flows in the option pricing calculations.

It is useful to compare Figure 7 to the "standard" R&D model, which typically assumes natural evolution from basic research to exploratory development to advanced development. Within DoD, these stages are termed 6.1, 6.2, and 6.3, with reference to budget categories. From Figure 7 it can be seen that this evolution is only "natural" to the extent that decisions regarding controls and resources are well planned and coordinated.

Inadequate planning and coordination can result in "time to decision" and "time to deployment" dominating overall "time to market." In other words, the actual time devoted to R&D can be a surprisingly small portion of the overall calendar time from initial concept to deployed capabilities. Certainly, this case study of ITS over the past 40+ years illustrates how long it can take for original investors—in this case, DoD—to see the benefits of their investments.

On the other hand, high school students have been benefiting from the resulting ITS for almost 20 years. In search of large populations for evaluating ITS, high school populations were attractive to the research community—and the somewhat unexpected primary beneficiaries of the investments in ITS. Of course, the possibility of unexpected beneficiaries receiving the greatest benefits has been quite common in S&T for many centuries [Burke, 1996].

6. OVERALL VALUE CREATION MODEL

As indicated in the explanation of Figure 7, this depiction represents a kernel that repeats many times in an overall S&T value stream. It repeats in part because of there being multiple investments, projects, and deployments over the many years typically associated with the value stream for a particular technology and/or capability. It also repeats because enabling technologies continue to evolve, most notably in recent years via frequent new generations of information technology.

These observations, in conjunction with lessons learned from many of our aforementioned studies, suggest a generalization of Figure 7 in terms of the overall model of value creation S&T shown in Figure 8. Note that to simplify this depiction, arrows between stages indicate the flow of value content, controls, and/or resources. Also note that both within and across generation flows are of interest.

The nature of the value flows is quite multi-faceted. The flow from investment to R&D includes money, motivation, encouragement, and community. Thus, sponsors do much more than simply write checks. They attract talent and build intellectual communities that foster creation of knowledge and competencies.

The flow from R&D to deployment includes technology, money, and people. Technology options can be in the form of prototypes, proofs of concepts, patents, or licenses. People embody knowledge and competencies that provide options also. Other studies have shown that such people-based options can fade in value when teams are dispersed because deployment does not dovetail with R&D [Ballhaus, 2000].

The flow from investment in one time period to investment in a later time period hopefully includes lessons learned about creating and managing balanced portfolios. The flow from R&D in one time period to the next includes knowledge, people, and community. Finally, the flow from deployment in one time period to the next includes best practices and people. In these ways, the value creation process moves beyond any particular generation of technology.

This value creation model can be described more formally as follows:

- The flow of value is a stochastic process in terms of content, money, time, and ultimate success.
- Processes generate content and consume money and time, all of which are random variables.

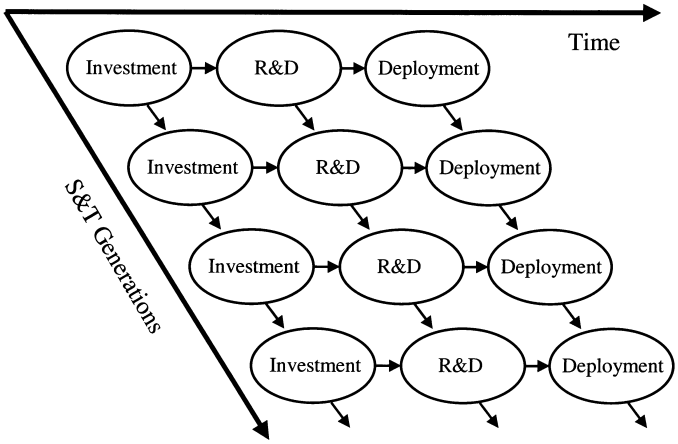

Figure 8. Overall model of S&T value creation.

- Success in process stage N results in transition to process stage $N + 1$; transitions from process stage $N(t)$ to $N(t + 1)$ are also possible.
- Transitions, i.e., successes, are uncertain and, in finite time, may not occur, potentially resulting in lost investments.
- A new S&T generation *may* preempt the current generation, resulting in termination of that generation's processes.
- Lessons learned, fundamental knowledge, and best practices *may* transition from one generation to the next generation.

Translation of these premises into an operational model is beyond the scope of this article. However, simple observation of Figure 8 in conjunction with these premises suggests several implications and hypotheses. Evaluation of these hypotheses will involve both this model and continuing empirical assessments.

To the extent that the time between S&T generations is less than the duration of value streams within generations, the probability of successful deployment will decrease. Variability of interarrival times and/or durations provide opportunities for successes to "slip through" despite mismatched means. In other words, while structural mismatches may mitigate against success, occasional successes will happen, perhaps leading to misperceptions that a best practice has been found.

It is also quite possible for new systems to be deployed with old technologies—those from older S&T generations. This occurs with military systems quite frequently. It happens much less often for computers and communications systems, for instance. When this does happen, value degrades due to lost innovation. Such losses of value, for this reason and others, can be incorporated into the model in Figure 8.

To the extent that knowledge transitions from one generation to the next, durations of value streams will decrease and probability of successful deployment increase. Difficulties due to mismatches between the characteristics of S&T generations and value streams can be alleviated by accelerating value streams via organizational learning. In the absence of such learning, success rates will be difficult to improve.

To the extent that management practices decrease time wasted in value streams, durations of value streams will decrease and probability of successful deployment increase. Decreasing "time to decision," as well as coordinating investment and deployment decisions should decrease both the mean and variance of the duration of value streams. This should increase the yield of successes.

As indicated earlier, full evaluation of these hypotheses will be conducted using the aforementioned model as well as selected empirical results. We certainly expect a range of new insights to emerge in this process. Our overarching sense is that the structural properties of S&T value streams strongly impact the returns on investments. Champions, motivation, leadership, and related phenomena undoubtedly are also important factors. However, structural characteristics—that is, the "S&T system"—may limit the leverage gained from such factors.

It is useful to return to our earlier observation of how champions can be deciding factors in transitioning technologies to use [Rouse and Boff, 1994]. Despite their significant value, champions and leaders cannot completely eliminate all adverse effects of system structure. If this were true, system structure would not matter because champions and leaders would always assure the best results regardless of inhibiting structural constraints. However, value creation is not "simply" a matter of good intentions and hard work. System design does matter.

Indeed, we see the concepts and methods described here as providing an initial basis for redesigning value streams and overall organizations. The notions of value flow through multiple stages, different types of “users” at each stage, and options being created upstream for possible exercising downstream are central to addressing such redesign efforts. Appropriate support mechanisms at each stage and across stages are essential to realizing the benefits of redesign.

Once the proposed model is elaborated and validated against a range of empirically derived phenomena, it should prove quite useful for conducting a range of tradeoff analyses involving risks, resources, and time. One of the tradeoffs of interest concerns how many investments are initiated, as well as the stage-gate parameters that are used to weed out expected losers. Backing only one idea is very risky unless, of course, you happen to be right. Backing too many ideas results in spreading resources too thinly.

Another tradeoff involves balancing under-funding that results in no viable options vs. overfunding that results in options with negative net values. The optimal investment level depends on the uncertainties involved and, of course, possible returns. This type of analysis can enable “backcasting” of R&D investment levels [Rouse, 2001].

Other types of tradeoffs involve time. As indicated above, arrivals of new S&T generations result in fielding lower value solutions, at least in terms of innovation. Consequently, it makes sense to invest a portion of the resources in speeding up R&D processes. A key question is what portion of R&D resources should be spent on improving these processes rather than on primary R&D.

7. CONCLUSIONS

In our earlier article, organizational value strategies were conceptualized in terms of three dimensions: quality, productivity, and innovation. Focusing on research and development (R&D) organizations, we considered how to align technology value strategies with overall enterprise value strategies. We also elaborated the change management issues of central import to successful implementation of value strategies.

This article has expanded the purview of R&D by considering it in the wider context of science and technology (S&T). This expansion involves consideration of the broad community of investors, sponsors, investigators, adopters, and end-users. This wide range of stakeholders adds value in a variety of ways, resulting in what are termed value streams.

We have focused in this article on elaborating and formalizing S&T value streams. This formulation was evaluated in the context of a case study of computer-based intelligent tutoring systems. The value streams identified in this context spanned several decades of S&T investments, R&D in numerous organizations, and deployments in a variety of school settings.

Insights gained from this case study enabled proposing a general model of value creation in S&T , involving a range of formal assertions about the structural characteristics of the S&T system. The phenomena embodied in this model suggested several central hypotheses. Model-based and empirical approaches to evaluating these hypotheses were outlined.

An obvious question regarding our conclusions concerns the extent to which they are premised on one, possibly idiosyncratic, case study. Fortunately, our earlier case study of Cockpit Automation Technology (CAT) also provides ample evidence of the phenomena identified in the ITS case study [Rouse, Boff, and Thomas, 1997]. In particular, the Air Force’s investments in CAT resulted in substantial payoffs in directions other than originally intended.

CAT also involved continued reinvestments in new generations of technologies, which profoundly affected the productivity of the initiative. Deployment of CAT also suffered from lack of coordination of decisions regarding investments and deployment. On the other hand, CAT fostered many spin-off ideas and competencies independent of the particular cockpit design environment created. Unlike ITS, the range of impact sought with CAT was quite focused.

The value of S&T is in its impact relative to required investments. S&T value streams create technology options in the form of knowledge, competencies, prototypes, patents, etc. The overall enterprise needs the people and options yielded by these investments to enable alternative futures while also improving the efficiency and effectiveness of current products and processes.

By formalizing the notion of value streams, we can gain understanding of how to better manage them. This includes both improving the characteristics within each generation and assuring organizational learning across generations. This should result in continually increasing the value created by S&T relative to the investments required.

REFERENCES

J.R. Anderson, A.T. Corbett, K.R. Koedinger, and R. Pelletier, Cognitive tutors: Lessons learned, J Learning Sci 4(2) (1995), 167–207.

W. Ballhaus (Editor), Science and technology and the Air Force vision, U.S. Air Force Scientific Advisory Board, Washington, DC, 2000.

D. Bitzer, P. Braunfield, and W. Lichtenberger, PLATO: An automatic teaching device, IRE Trans Ed 4 (1961), 157–161.

F.P. Boer, Financial management of R&D: 2002. Res Technol Manage 45(4) (2002), 23–35.

J. Burke, The pinball effect: How Renaissance water gardens made the carburetor possible and other journeys through knowledge, Little, Brown, Boston, 1996.

H.L. Burns, J.W. Parlett, and C.A. Luckhardt (Eds), Intelligent tutoring systems: Evolutions in design, Erlbaum, Hillsdale, NJ, 1991.

J.R. Carbonell, AI in CAI: An artificial intelligence approach to computer-assisted instruction, IEEE Trans Man-Machine Syst 11 (1970), 190–202.

A.T. Corbett, K.R. Koedinger, and W. Hadley, "Cognitive tutors: From the research classroom to all classrooms," Technology enhanced learning: Opportunities for change, P.S. Goodman (Editor), Erlbaum, Mahwah, NJ, 2002.

DoD, Department of Defense strategic plan for advanced distributed learning: Report to the 106th Congress, Office of the Deputy Undersecretary of Defense for Readiness and Training, Washington, DC, 1999.

J.D. Fletcher, "Intelligent tutoring systems: Then and now," Advanced Training Technologies and Learning Environments: Proceedings of the Workshop, March 9–10, 1999, A.K. Noor and J.B. Malone (Editors), NASA/CP-1999-209339, NASA Langley Research Center, Hampton, VA, 1999, pp. 83–104.

J.D. Fletcher, personal communication, December 12, 2001.

J.D. Fletcher, "Evidence for learning from technology-assisted instruction," Technology applications in education: A learning view, H.F. O'Neil Jr. and R. Perez (Editors),. Erlbaum, Hillsdale, NJ, 2002..

J.D. Fletcher and M.R. Rockway, "Computer-based training in the military," Military contributions to instructional technology, J.A. Ellis (Editor), Praeger, New York, 1986.

R. Gagne and L.J. Briggs, Principles of instructional design, Holt, Rinehart and Winston, New York, 1974.

W.C. Kessler, Implementing lean thinking, Inf Knowledge Syst Manage 1(2) (1999), 99–103.

D.H. Krantz, R.D. Atkinson, R.D. Luce, and P. Suppes (Editors), Contemporary developments in mathematical psychology, Freeman, San Francisco, 1974.

A. Kusiak and N. Larson, "Concurrent engineering," Handbook of systems engineering and management, A.P. Sage and W.B. Rouse (Editors), Wiley, New York, 1999, Chap. 9.

G.A. Miller, The magic number seven, plus or minus two: Some limits on our capacity for processing information, Psychol Rev 63(2) (1956), 81–97.

National Research Council (NRC), Technology for the United States Navy and Marine Corps, 2000–2035, Vol. 4: Human resources, Naval Studies Board, Washington, DC, 1997.

A. Newell and H.A. Simon, Human problem solving, Prentice-Hall, Englewood Cliffs, NJ, 1972.

F.G. Patterson, Jr., "Systems engineering life cycles: Life cycles for research, development, test, and evaluation; acquisition; and planning and marketing," Handbook of systems engineering and management, A.P. Sage and W.B. Rouse (Editors), Wiley, New York, 1999, Chap. 1.

M.C. Polson and J.J. Richardson (Editors), Foundations of intelligent tutoring systems, Erlbaum, Hillsdale, NJ, 1988.

J. Pontin, The future of electronic education, Red Herring (January 2002), 100.

J. Psotka, L.D. Massey, and S.A. Mutter (Editors), Intelligent tutoring systems: Lessons learned, Erlbaum, Hillsdale, NJ, 1988.

J.W. Regian and V.J. Shute, (Editors), Cognitive approaches to automated instruction, Erlbaum, Hillsdale, NJ, 1992.

W.B. Rouse (Editor), Advances in man-machine systems research, JAI Press, Greenwich, CT, 1987, Vol. 3.

W.B. Rouse, Backcasting R&D investments, Int Symp Forecasting, Callaway Gardens, Georgia, June, 2001.

W.B. Rouse and K.R. Boff, Technology transfer from R&D to applications, Armstrong Research Laboratory, Wright-Patterson AFB, OH, December 1994.

W.B. Rouse and K.R. Boff, R&D/technology management: A framework for putting technology to work, IEEE Trans Syst Man Cybernet C 28(4) (1998), 501–515.

W.B. Rouse and K.R. Boff, Making the case for investments in human effectiveness, Inf Knowledge Syst Manage 1(3) (1999), 225–247.

W.B. Rouse and K.R. Boff, Strategies for value: Quality, productivity, and innovation in R&D/technology organizations, Syst Eng 4(2) (2001), 87–106.

W.B. Rouse and N.M. Morris, On looking into the black box: Prospects and limits in the search for mental models, Psychol Rev 100(3) (1986), 349–363.

W.B. Rouse, K.R. Boff, and B.G.S. Thomas, Assessing cost/benefits of R&D investments, IEEE Trans Syst Man Cybernet A 27(4) (1997), 389–401.

W.B. Rouse, B.G.S. Thomas, and K.R. Boff, Knowledge maps for knowledge mining: Application to R&D/technology management, IEEE Trans Syst Man Cybern C 28(3) (1998), 309–317.

W.B. Rouse, C.W. Howard, W.E. Carns, and E.J. Prendergast, Technology Investment Advisor: An options-based approach to technology strategy, Inf Knowledge Syst Manage 2(1) (2000), 63–81.

J.T. Rowell and E.R. Streicht, The SAGE system training program for the Air Force Defense Command, Hum Factors 6 (1964), 537–548.

A.P. Sage, Systems management for information technology and software engineering, Wiley, New York, 1995.

A.P. Sage and W.B. Rouse (Editors), Handbook of systems engineering and management, Wiley, New York, 1999.

B.F. Skinner, Behavior of organisms, Appleton-Century-Crofts, New York, 1938.

D.H. Sleeman and J.S. Brown, Intelligent tutoring systems, Academic, London, 1982.

P. Suppes (Editor), University-live computer-assisted instruction at Stanford: 1968–1980, Institute for Mathematical Studies in the Social Sciences, Stanford, CA, 1981.

TutorTek, Fundamental skills training project: Evaluation summary, http://www.tutortek.com/docs/fstoutc.htm, 2001.

J.B. Watson, Behavior, Henry Holt, New York, 1914.

J.L. Wheeler and J.W. Regian, The use of a cognitive tutoring system in the improvement of the abstract reasoning component of word problem solving, Comput Hum Behav 15 (1999), 243–254.

J.P. Womack and D.T. Jones, Lean thinking: Banish waste and create wealth in your corporation, Simon and Schuster, New York, 1996.

Bill Rouse is the H. Milton and Carolyn J. Stewart Chair of the School of Industrial and Systems Engineering at the Georgia Institute of Technology. He is responsible for leadership of the school, as well as development and management of its human and financial resources. He is also founder and a principal in Enterprise Support Systems. ESS provides software tools for strategic management, as well as consulting and training services in use of these tools. Rouse has more than 30 years of experience in research, education, management, marketing, and engineering related to individual and organizational performance, decision support systems, and information systems. In these areas, he has consulted with more than 100 large and small enterprises in the private, public, and nonprofit sectors, where he has worked with several thousand executives and senior managers. His expertise includes individual and organizational decision making and problem solving, as well as design of organizations and information systems. Rouse has written hundreds of articles and book chapters, and has authored many books, including most recently *Essential Challenges of Strategic Management* (Wiley, 2001), the award-winning *Don't Jump to Solutions* (Jossey-Bass, 1998), and *Start Where You Are* (Jossey-Bass, 1996). He is co-editor of *Handbook of Systems Engineering and Management* (Wiley, 1999) and edited the eight-volume series *Human/Technology Interaction in Complex Systems* (Elsevier). Among many advisory roles, he has served as Chair of the Committee on Human Factors of the National Research Council and as a member of the U.S. Air Force Scientific Advisory Board. Rouse is a member of the National Academy of Engineering, as well as a fellow of the Institute of Electrical and Electronics Engineers (IEEE), the Institute for Operations Research and Management Science, and the Human Factors and Ergonomics Society. He has received the Joseph Wohl Outstanding Career Award and the Norbert Wiener Award from the IEEE Systems, Man, and Cybernetics Society; a Centennial Medal and a Third Millennium Medal from IEEE; and the O. Hugo Schuck Award from the American Automation Control Council. He is listed in *Who's Who in America, Who's Who in Engineering*, and other biographical literature, and has been featured in publications such as *Manager's Edge*, *Vision*, *Book-Talk*, *The Futurist*, *Competitive Edge*, *Design News*, *Quality and Excellence*, and *IIE Solutions*. Rouse has served in a variety of leadership roles in other companies and on the faculty of the University of Illinois at Urbana-Champaign. He also has served in visiting positions on the faculties of Delft University of Technology in The Netherlands and Tufts University. He received his B.S. from the University of Rhode Island, and his S.M. and Ph.D. from the Massachusetts Institute of Technology.

Kenneth R. Boff, Ph.D. serves as Chief Scientist of the Human Effectiveness Directorate, Air Force Research Laboratory, Wright-Patterson Air Force Base, Ohio. In this position, he has responsibility for the technical direction and quality of a broad multidisciplinary R&D portfolio encompassing human-engineering of complex systems, training, safety, protection, and deployment logistics. He is best known for his work on understanding and remediating problems in the transition of research to applications in the design and acquisition of complex human-systems. Holder of a patent for rapid communication display technology, Boff has authored numerous articles, book chapters, and technical papers, and is co-editor of *System Design* (1987), senior editor of the two-volume *Handbook of Perception and Human Performance* (1986), and the four-volume *Engineering Data Compendium: Human Perception and Performance* (1988). Boff actively consults and provides technical liaison with government agencies, international working groups, universities, and professional societies. He is founder and technical director of the Department of Defense Human System Information Analysis Center, and founding member and chair of the DoD Reliance Human-Systems Interface Technology Panel. Currently, he is serving part-time on the faculty of the Georgia Institute of Technology, School of Industrial and Systems Engineering as an Edenfield Executive in Residence. Internationally, he serves as the U.S. National Coordinator and NATO chair for the human factors technology area. Boff is a Fellow of the Human Factors and Ergonomics Society and the International Ergonomics Association.